Tropical Cyclone Structure and Intensity Change Related to Eyewall Replacement Cycles and Annular Storm Formation, Utilizing Objective Interpretation of Satellite Data and Model Analyses

James P. Kossin
Cooperative Institute for Meteorological Satellite Studies
University of Wisconsin–Madison
1225 W. Dayton St., Room 205
Madison, WI 53706
phone: (608) 265-5356 fax: (608) 262-5974 email: kossin@ssec.wisc.edu

David S. Nolan
Division of Meteorology and Physical Oceanography
Rosenstiel School of Marine and Atmospheric Science
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
phone: (305) 421-4930 fax: (305) 421-4696 email: dnolan@rsmas.miami.edu

Award Number: N00014-07-1-0163 (Kossin), N00014-07-1-0164 (Nolan)

LONG-TERM GOALS

This project aims toward increasing our understanding of the dynamics of secondary eyewalls in tropical cyclones and our ability to forecast their formation and associated intensity changes. This is being accomplished through a synergistic combination of theoretical, empirical, and numerical modeling approaches. We expect to apply our results to the construction of objective algorithms that will be transitioned to operations to provide forecasters with new tools for improved forecasting of tropical cyclone structure and intensity.

OBJECTIVES

1) Elucidate the internal vortex dynamics associated with secondary eyewall formation (SEF) with a unique combination of basic theory, idealized models, and full-physics models.
2) Identify and quantify the environmental factors related to SEF through application of reanalysis fields and satellite imagery.
3) Construct objective algorithms to diagnose SEF (and associated intensity changes) in real-time.

APPROACH

We are following a multi-pronged approach that incorporates basic theory, idealized modeling, full-physics modeling, and empirical/statistical analyses. Guidance for the empirical/statistical analyses is

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **Tropical Cyclone Structure And Intensity Change Related To Eyewall Replacement Cycles And Annular Storm Formation, Utilizing Objective Interpretation Of Satellite Data And Model Analyses**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Wisconsin-Madison,Cooperative Institute for Meteorological Satellite Studies,1225 W. Dayton St., Room 205,Madison,WI,53706**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project aims toward increasing our understanding of the dynamics of secondary eyewalls in tropical cyclones and our ability to forecast their formation and associated intensity changes. This is being accomplished through a synergistic combination of theoretical, empirical, and numerical modeling approaches. We expect to apply our results to the construction of objective algorithms that will be transitioned to operations to provide forecasters with new tools for improved forecasting of tropical cyclone structure and intensity.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

derived from the basic theory and idealized modeling results. The results of the empirical/statistical analyses then provide guidance for a systematic suite of full-physics modeling experiments. Our empirical/statistical approach involves composite analyses and Principal Component Analyses (PCA) of storm-centered environmental fields and satellite imagery. We have developed an objective classification scheme that diagnoses and forecasts SEF. The classification algorithm was developed in a Bayesian framework. The idealized modeling part of this work has utilized a diagnostic model based on the Eliassen transverse circulation model. The diagnostic analyses using the Eliassen model have been extended to unsteady dynamics using a time-dependent, nonhydrostatic model of symmetric vortex dynamics. The full-physics modeling part of this project is being wrapped up and involves idealized simulations of tropical cyclones designed to reproduce eyewall replacement cycles and related processes.

PUBLICATIONS RESULTING FROM THIS WORK

Rozoff, C. M., W. H. Schubert, and J. P. Kossin, 2008: Some dynamical aspects of tropical cyclone concentric eyewalls. *Q. J. R. Meteorol. Soc.*, **134**, 583–593.

Kossin, J. P., and M. Sitkowski, 2009: An objective model for identifying secondary eyewall formation in hurricanes. *Mon. Wea. Rev.*, **137**, 876—892.

Rozoff, C. M., J. P. Kossin, and D. S. Nolan, 2009: Dynamical mechanisms for secondary eyewall formation in a high-resolution mesoscale model simulation of an intense tropical cyclone. *Mon. Wea. Rev., in preparation.*

SELECTED PRESENTATIONS

UW-Madison Department of Atmospheric and Oceanic Sciences
Christopher Rozoff "Dynamical mechanisms for secondary eyewall formation in a high-resolution mesoscale model simulation of an intense tropical cyclone" (2009)

University of Miami Rosenstiel School of Marine and Atmospheric Science
Christopher Rozoff "An overview of the emerging understanding of concentric eyewalls in hurricanes" (2009)

28th Conference on Hurricanes and Tropical Meteorology (Amer. Met. Soc.)
Christopher Rozoff "Some dynamical aspects of tropical cyclone concentric eyewalls" (2008)

RESULTS

(a) Numerical mesoscale simulations of eyewall replacement cycles

Using the Weather Research Forecast (WRF) model (Skamarock et al. 2005), we have investigated hypotheses related to secondary eyewall formation in idealized numerical modeling simulations. The idealized simulations are similar in design to a recent study of Nolan (2007), which use observed thermodynamic soundings from the Atlantic hurricane season. In this set of idealized numerical experiments, a weak, mid-level vortex is embedded in a mean flow and/or mean shear flow on either

the *f*-plane or β–plane. A large outer domain is used with 18 km horizontal grid spacing.   Vortex following grids containing grid spacing of 6 and 2 km are nested within this outer grid.

Unfortunately, in the attempt to obtain a large sample size of numerical experiments demonstrating secondary eyewall formation, only one idealized simulation successfully produced an eyewall replacement cycle-like event. Nonetheless, future modeling efforts should continue to examine the potentially wide variety of physical conditions that constitute necessary and/or sufficient conditions for eyewall expansion processes. The secondary eyewall formation simulation was carried out on the β–plane. This vortex rapidly intensifies and reaches an approximate steady state during the first day. On the third day, an eyewall replacement cycle commences.   Figure 1 shows a Hovmoller diagram of the mid-level vertical velocity on the third day of the simulation, which captures the eyewall replacement cycle and ultimate eyewall expansion. This particular cycle shows the outer eyewall formation occurring out at r = 45 – 60 km around 5 – 6 h. This feature does not become dominant until it has contracted inward to about r = 35 – 45 km 10 – 12 h into that simulation day. Thus, a classic longer-lived double eyewall structure with a well-defined moat configuration is not seen in this particular simulation, but many essential aspects of radial structure changes are displayed in this instance.

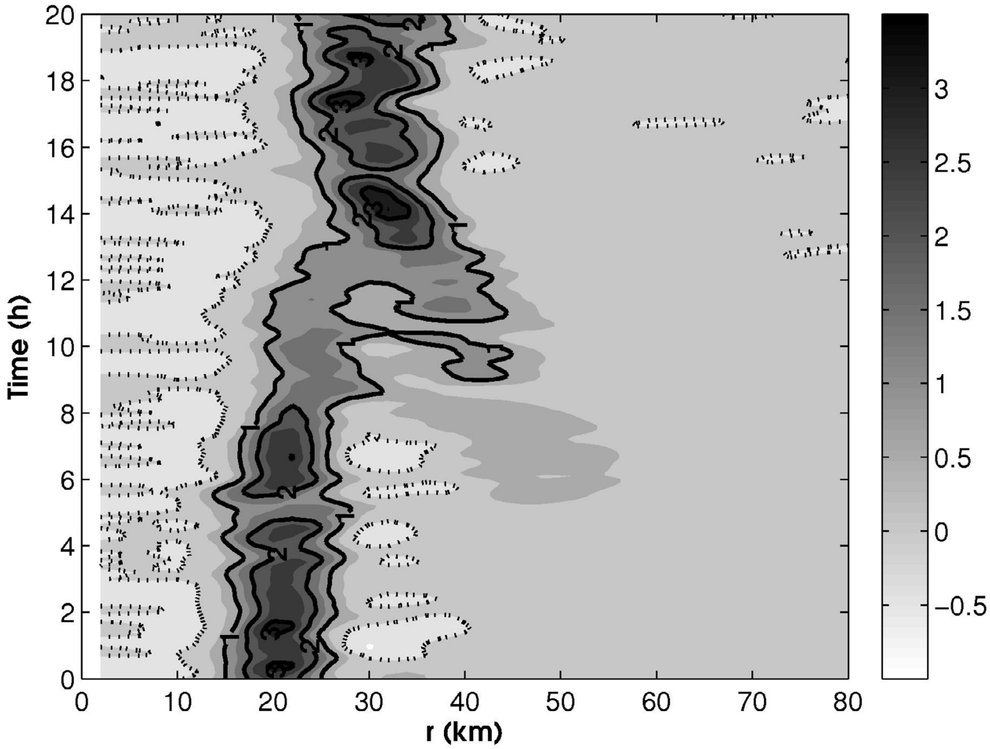

Figure 1. Radius-time Hovmoller diagram of vertical motion (m s^{-1}) at z = 5 km on the third day of simulation.

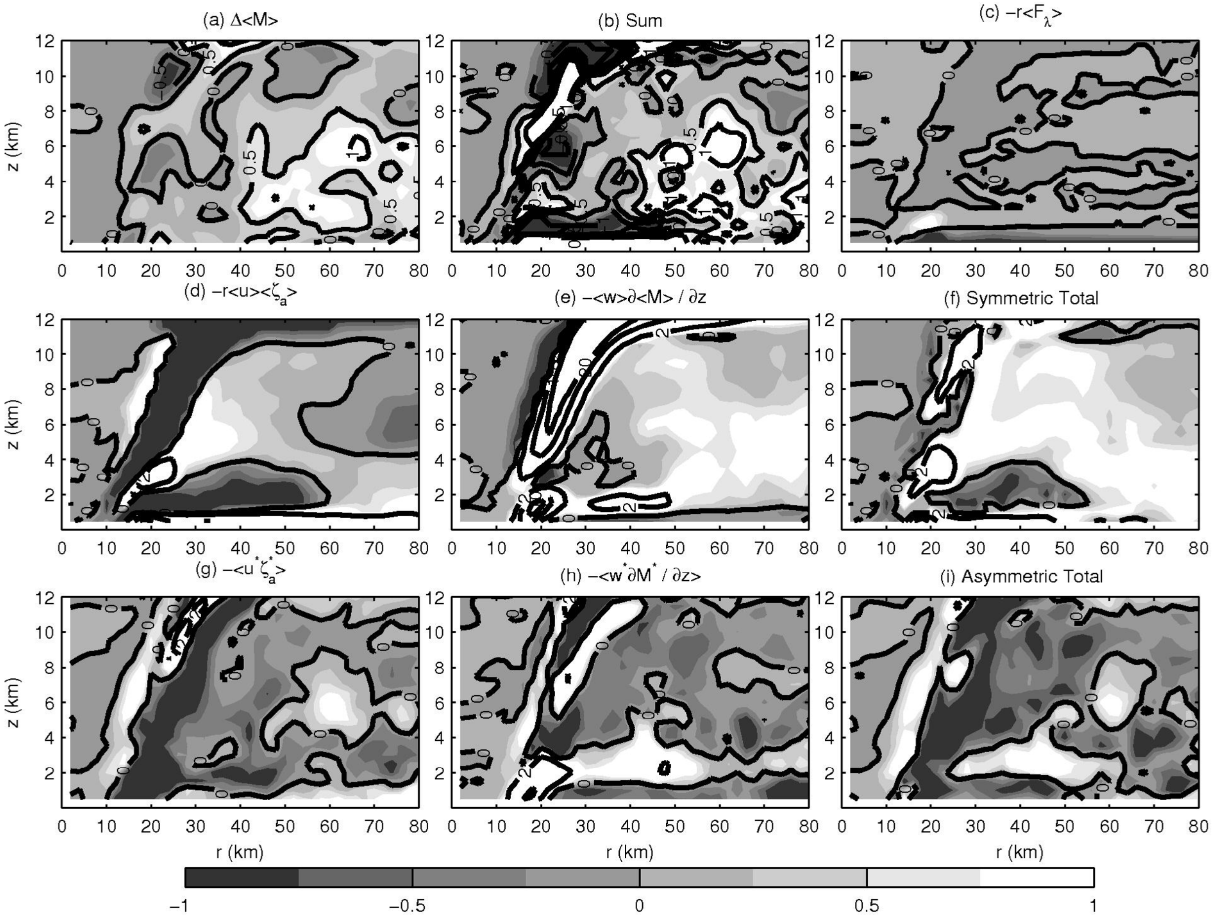

Figure 2. Various terms of an angular momentum budget (in cylindrical-physical height coordinates) for t = 6 to 7 h. The above radius-height panels show (a) actual change in azimuthally-average (brackets represents an azimuthal average) angular momentum in the model simulation, (b) the sum of the terms in the angular momentum budget equation, (c) the total frictional contribution to (b), the mean (d) radial and (e) vertical advection contributions to (b), (f) the total symmetric contribution (c+d+e) to (b), the asymmetric (g) radial and (h) vertical advection components of (b), and (i) the total asymmetric contribution (g+h) to (b). Angular momentum changes are expressed in units of 10^5 m^2 s^{-1} h^{-1}.

We have investigated the mechanisms that lead to the simulated eyewall expansion process from a variety of perspectives. An angular momentum budget (in cylindrical-physical height coordinates) can shed some light into the expansion of the tangential wind field. Figure 2 provides a summary of an hour-long budget (using a 6-min output frequency) when the outer eyewall was becoming detectable in the vertical velocity field (t = 6-7 h). Figure 2a shows the change in angular momentum ($M = ½ fr^2 + rv$) over the hour-long period. Figure 2b shows the sum of the advection and friction terms that should come close to reproducing the simulation changes seen in Fig. 2a. There are some errors near the inner-core within the boundary layer and near the strong gradients of the primary eyewall, but by and large, the budget calculation is successful, especially in the vicinity of the forming outer eyewall (r = 40-60 km). From the perspective of this angular momentum budget, the expansion of the tangential wind field during the process is dominated by the axisymmetric mean transverse circulation. This

transverse circulation is associated with the enhanced diabatic heating erupting in the vicinity of the forming outer eyewall. Asymmetric activity does slightly contribute to the expansion of the wind field as well, particularly at low levels. Note that a low-level negative potential vorticity gradient extends from the primary eyewall to well beyond r = 100 km, so low-level vortex Rossby wave activity is supported in this region, but it is not clear whether this is having a direct or indirect role. Other hour long budgets during the eyewall replacement cycle remain consistent with this result, although this time period captures the most dramatic changes in angular momentum.

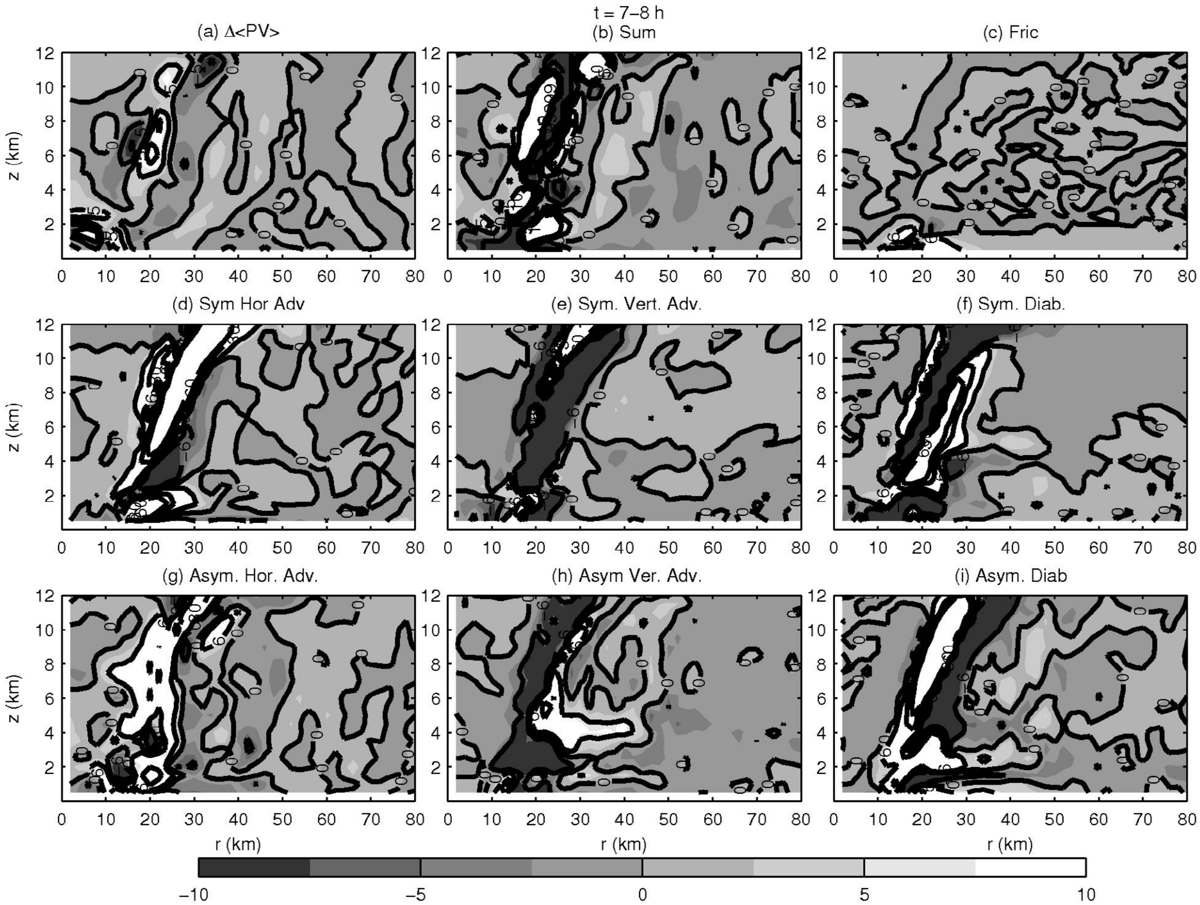

Figure 3. Various terms of the potential vorticity budget for t = 7 to 8 h. The above radius-height panels show (a) actual change in azimuthally-average potential vorticity in the model simulation, (b) the sum of the terms in the potential vorticity budget equation, (c) the total frictional contribution to (b), the mean (d) radial and (e) vertical advection contributions to (b), (f) the symmetric diabatic heating contribution to (b), the asymmetric (g) radial and (h) vertical advection components of (b), and (i) the asymmetric asymmetric diabatic heating contribution to (b). Potential vorticity rates of change are expressed in units of 10^6 m^2 kg^{-1} K^{-1} s^{-1} h^{-1} (PVU h^{-1}).

Potential vorticity at vertical depth also increases as the outer eyewall develops, but the majority of this increase lags the concentrated diabatic heating associated with the incipient outer eyewall and its increasing angular momentum. A potential vorticity budget (in cylindrical-physical height coordinates) for the period between 7 and 8 h is presented in Fig. 3. Once again, the actual simulated change in potential vorticity finds its best agreement with the sum of budget terms outside of the

primary eyewall (compare Figs. 3a and b). Potential vorticity is increasing in the tilted outer ring of convection (*r* = 30-50 km) during this time frame. According to the budget, asymmetric processes, particularly diabatic heating and vertical advection, contribute to most of the potential vorticity increases in the outer eyewall during the formation of the outer eyewall. This result does not appear to negate leading hypotheses for secondary eyewall formation, whether the process is initiated by wave-mean flow interactions involving vortex Rossby waves or the vortex's dynamical adjustment to the concentration of potential vorticity by sustained diabatic heating occurring in the asymmetric rainband activity.

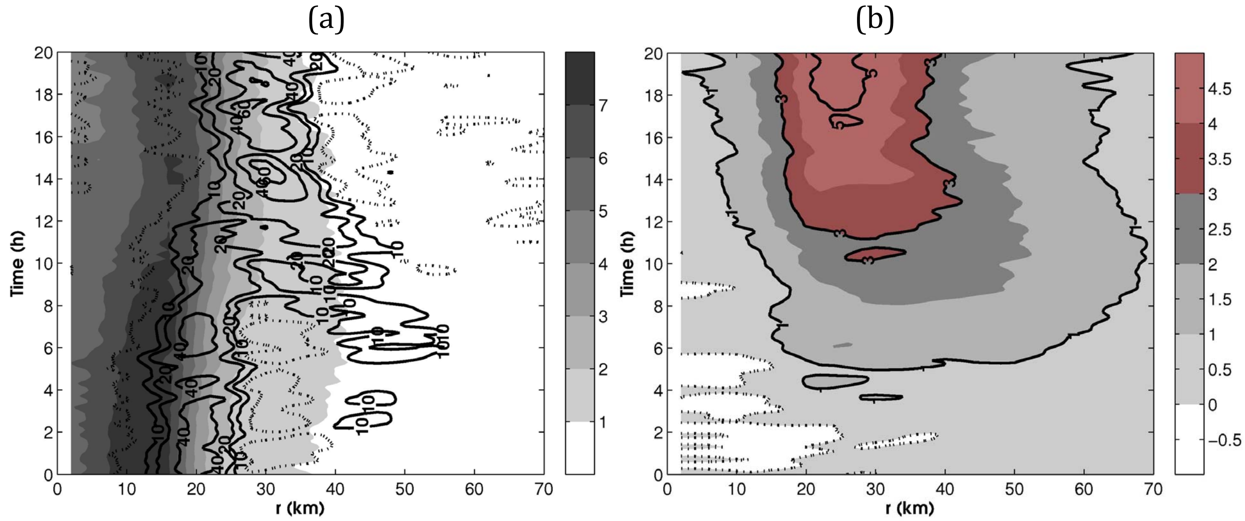

Figure 4. (a) Inertial stability parameter ($([\langle f\rangle + \langle\zeta\rangle][\langle f\rangle + 2\langle v\rangle/r])^{-1/2}$ at z = 0.5 km (shaded; units of 10^{-3} s^{-1}) and condensational heating (contoured; K h^{-1}) at z = 4 km. (b) Change in potential temperature from t = 0 h at z = 7.5 km.

Thus, the importance of diabatic heating in driving the development of the outer eyewall is clearly demonstrated in the budget calculations. The low-level potential vorticity and inertial stability expand outward as the outer eyewall develops. Concentrated diabatic heating increasingly coincides with the enhanced region of inertial stability (Fig. 4a) as the outer eyewall contracts inward. The condensational heating increases in intensity and in total tropospheric depth in the outer ring as it moves into the higher inertial stability and the original eyewall weakens. At the same time, the higher inertial stability spreads outward toward the enlarged eyewall. As diabatic heating meets up with the higher inertial stability, the efficiency of intensification of the contracting outer eyewall is expected to increase (e.g., Rozoff et al. 2008). Consistent with this balanced vortex perspective is the rapid increase in the intensity and expansion of the upper level warm core (Fig. 4b). This warm core particularly strengthens when the outer ring of diabatic heating coincides more closely to the region of higher inertial stability, likely a result of direct diabatic heating and since more of the transverse circulation generated by the diabatic heating is forced to sink and adiabatically warm near the eyewall.

The remaining questions addressed in this work (currently being prepared in a manuscript to be submitted soon) seek to resolve unambiguous mechanisms that focus the diabatic heating in the annular region that subsequently leads to the new eyewall. Questions to address in future research are far more wide ranging and should involve probing the different environmental conditions allowing the internal dynamics to facilitate certain eyewall configurations over others. In this regard, we have made

progress from an observational perspective, as described below in (c), but future theoretical and modeling research will shed further insight into these observational results.

(b) Idealized aspects of tropical cyclone concentric eyewalls

In Rozoff et al. (2008), the transverse circulation associated with eyewall replacement cycles was investigated. Particular emphasis was placed on the role of the radial distribution of inertial stability and diabatic heating. Analytical solutions were obtained by assuming an idealized, axisymmetric, barotropic vortex. Further numerical study of baroclinic vortex structures increased confidence in the generality of the results of this study. It was found that subsidence associated with the outer eyewall does not suppress the inner eyewall. Rather, subsidence associated with diabatic heating in the inner and outer eyewalls and the associated adiabatic warming in the moat are enhanced as inertial stability associated with the primary circulation increases in the moat and outer eyewall during an eyewall replacement cycle. It was also demonstrated that the diabatic heating associated with the inner eyewall more efficiently warms the cyclone's inner core than the diabatic heating associated with the outer eyewall. Therefore, as heating shifts from an inner eyewall to an outer eyewall, a hurricane undergoing an eyewall replacment cycle temporarily loses its ability to produce an intense, localized warm core.

(c) Empirical/statistical results; a secondary eyewall formation model

As described in Kossin and Sitkowski (2009), an empirical model based on a Bayesian probabilistic framework has been developed to diagnose and forecast secondary eyewall formation. The scheme uses mean axisymmetric environmental conditions and satellite-derived cloud structures as predictors and has been shown to be skillful. The features include a combination of storm-based variables such as current intensity and latitude, environmental variables such as vertical wind shear and middle- to upper-level relative humidity, and geostationary satellite infrared-based variables. The model has been demonstrated to be skillful when measured against the climatology defined by event counts, especially in the North Atlantic basin. As a consequence of this study, an informative climatology of conditions associated with secondary eyewall formation events was developed, shedding new light into theoretical and modeling aspects of the problem.

This statistical model shows great potential in improving operational forecasting of storm intensity and size changes. *The model is currently being transitioned into operations at the National Hurricane Center through the Joint Hurricane Testbed program.*

RELATED PROJECTS

Much of the database construction required for the empirical/statistical part of this project was performed by a PhD student under a NOAA grant (P.I. Kossin).

The transition of the Bayes forecasting scheme into operations is being funded through NOAA's Joint Hurricane Testbed program (P.I.s Kossin and Rozoff).

REFERENCES

Kossin, J. P., and M. Sitkowski, 2009: An objective model for identifying secondary eyewall formation in hurricanes. *Mon. Wea. Rev.*, **137**, 876—892.

Nolan, D. S., 2007: What is the trigger for tropical cyclogenesis? *Aust. Meteorol. Mag.*, **56**, 241-266.

Rozoff, C. M., W. H. Schubert, and J. P. Kossin, 2008: Some dynamical aspects of tropical cyclone concentric eyewalls. *Q. J. R. Meteorol. Soc.*, **134**, 583–593.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: *A Description of the Advanced Research WRF Version 2.* NCAR technical note 468+STR, 88 pp.